Mass Estimation of Merging Clusters of Galaxies

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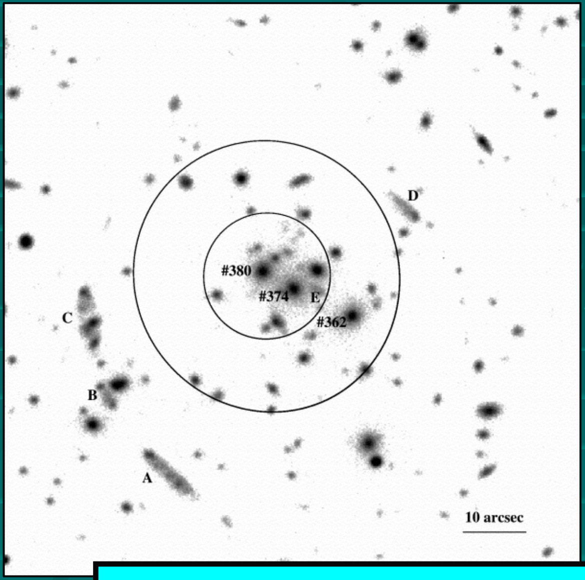
Introduction（1）

- Mass is one of the most important parameters to characterize astrophysical objects. This is especially true in many kinds of self-gravitating objects.
- Mass distribution in large scales such as clusters of galaxies
  - Dark matter property (self-interaction, MOND, etc)
  - Probes of structure formation
- However, It is not so easy to determine mass in an observational way.
- Cross-checks among different methods are important.
  - line-of-sight velocity distribution of member galaxies + Virial theorem or Jeans equation
  - X-ray observations (n_e, kT) + hydrostatic equilibrium
  - (strong and weak) gravitational lensing

Introduction（2）



However, inconsistent results are sometimes obtained from different methods for a single object.

CL 0024+17 (Ota et al. 2004)
Inconsistent results for mass within 200 kpc

- $M_X=0.84^{+0.20}_{-0.13}\times 10^{14}\, h_{50}^{-1}$ solar mass (Ota et al. 2004)
- $M_{lens}=3.117^{+0.004}_{-0.004}\times 10^{14} h_{50}^{-1}$ solar mass (Tyson et al. 1997)
- $M_{lens}=2.22^{+0.06}_{-0.06}\times 10^{14} h_{50}^{-1}$ solar mass(Broadhurst et al.2000

Some assumptions are necessary in mass estimation.
M_X (hydrostatic equilibrium, spherical symmetry,etc）、M_{lens}(axial symmetry, etc)、M_{virial}(dynamical equilibrium、isotropic velocity distribution,etc）

●These assumptions are not very good in clusters during or a few Gyr after mergers.
●It is not trivial how these systems will be overestimated or underestimated.

●Using N-body + hydrodynamical simulation data, “simulations of mass estimation” are performed, and the results are compared with “actual mass distribution” in the data.

Simulation Data
（N-body＋hydrodynamics）

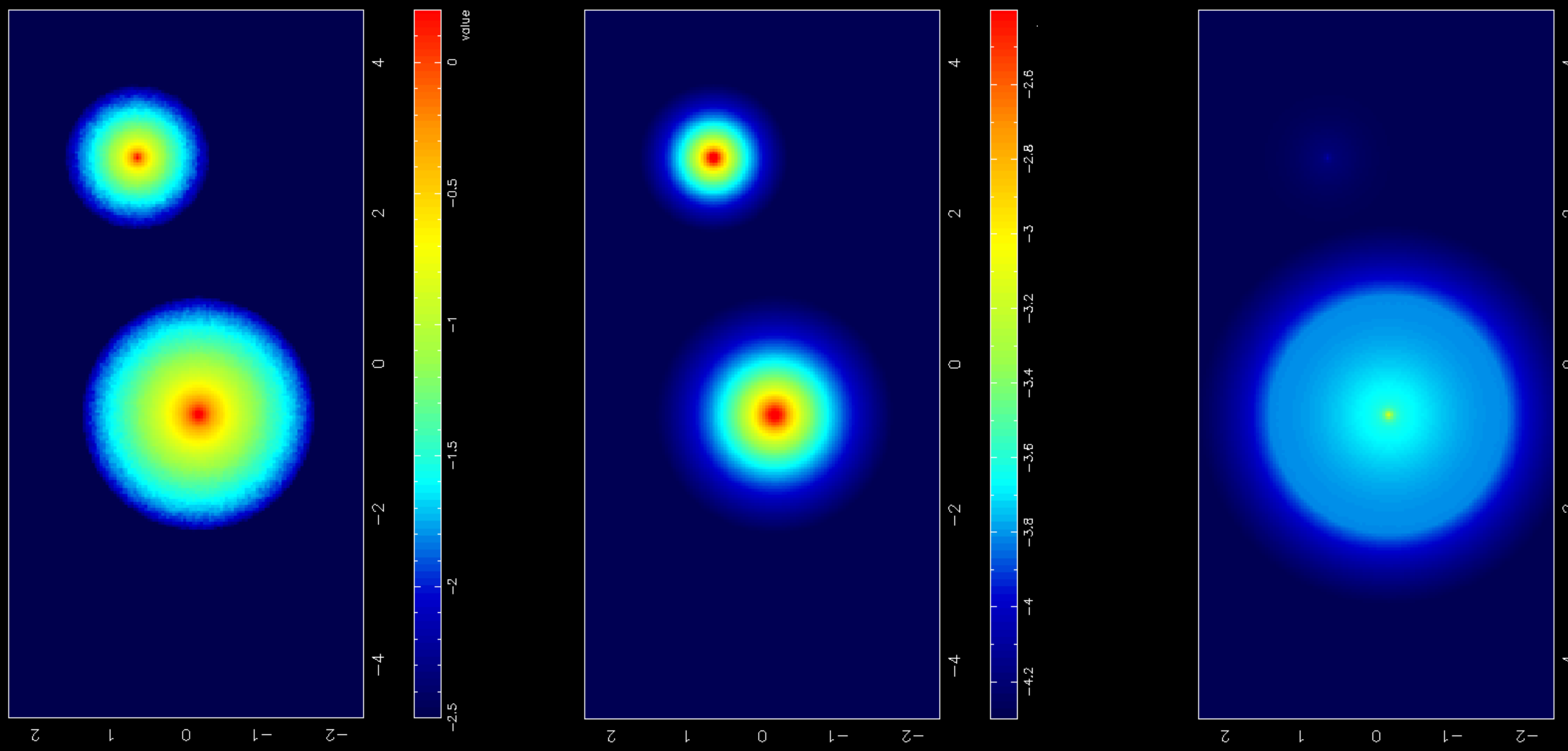
- N-body：Particle Mesh (PM) method
- self-gravity：FFT with isolated boundary conditions
- hydrodynamics：Roe TVD method
- number of grid points 256×128×128
- Number of particles 256×128×128 (≒4.2×10^6)
- VPP5000@NAOJ

Movies （mass ratio1:4, λ =0.05）

Mass distribution

Gas density

Gas temperature



Mass estimation with Virial theorem

- Clusters in the simulations are “observed” from certain directions.
- N_{samp} particles are randomly selected, and recognized as “galaxies whose line-of-sight velocity are observed”.
- Virial mass is calculated as follows.

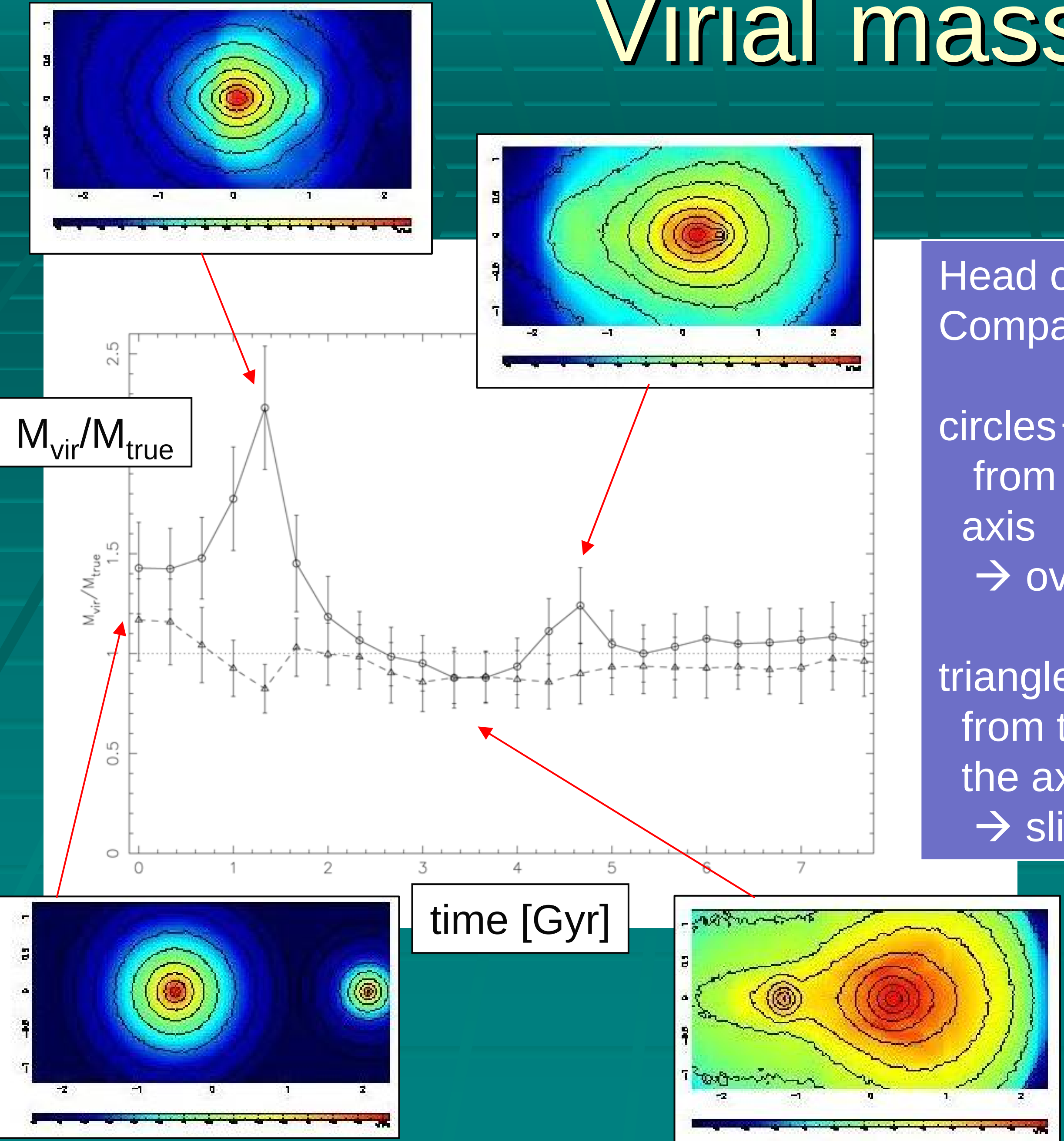
$$M_{\mathrm{VT}} = \frac{3\pi}{G}\sigma_{\mathrm{los}}^2 \left\langle \frac{1}{r} \right\rangle^{-1}$$

$$\left\langle \frac{1}{r} \right\rangle^{-1} = N_p \left(\sum_{i>j}^{N_p} \frac{1}{r_{ij}} \right)$$

r_{ij}: distance projected on the sky plain for particle pairs
σ_{los}:dispersion of line-of-sight velocity

- We estimate virial mass for different 100 sets of “member galaxies”, and calculate mean and variance of the virial mass.

Virial mass : results



Head on merger with mass ratio 1 : 4
Comparison between M_{vir} and M_{true}

circles+real lines:
from the direction along the collision axis
→ overestimate

triangles+dashed lines :
from the direction perpendicular to the axis
→ slightly underestimate

Mass Estimation with X-ray Data

- Assuming that clusters in simulations are “observed” , X-ray surface brightness maps and emission-weighted temperature maps are made.
- Radial profiles of X-ray surface brightness $I_x(R)$, and temperature T(R) are made.
- Density profiles ρ (r) are calculated from $I_x(R)$ in a standard deprojection technique.
- Both ρ (r) and T(r) are fitted with β -model.
- Assuming hydrostatic equilibrium, the mass profiles are calculated as follows,

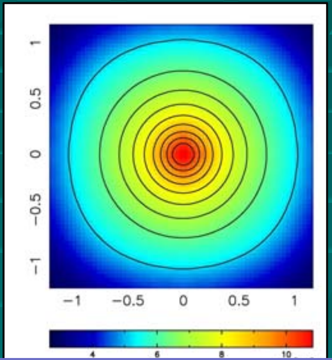
$$M_r = -\frac{k_{\rm B} T_{\rm g} r}{G \mu m_{\rm p}} \left(\frac{d \ln \rho_{\rm g}}{d \ln r} + \frac{d \ln T_{\rm g}}{d \ln r} \right)$$

Mass Estimation with X-ray Data: Results

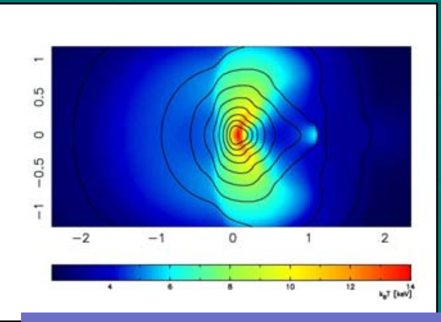
Dotte

Solid lines: M_X/M_{real}
Dotted lines: 1 asterisks: M_{virial}/M_{real}

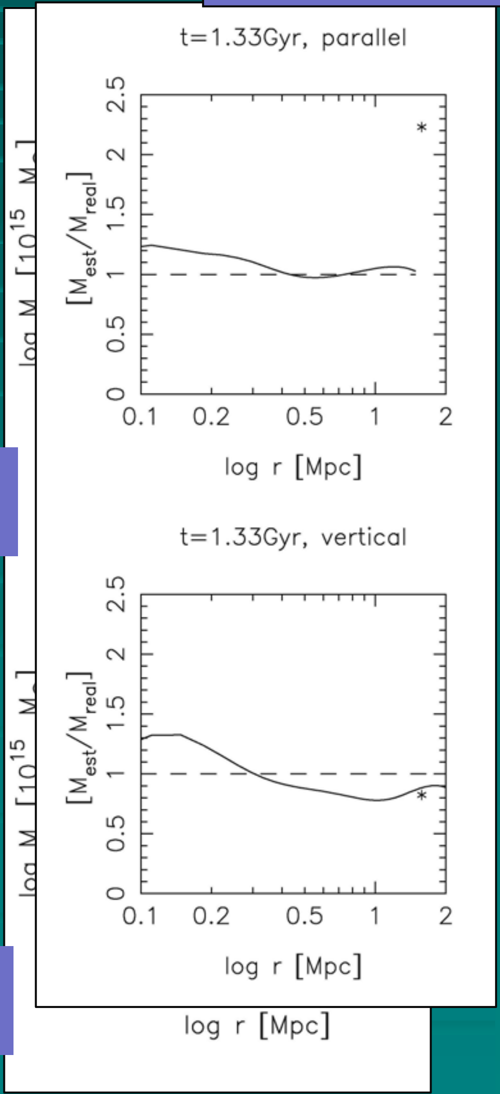
During core passage

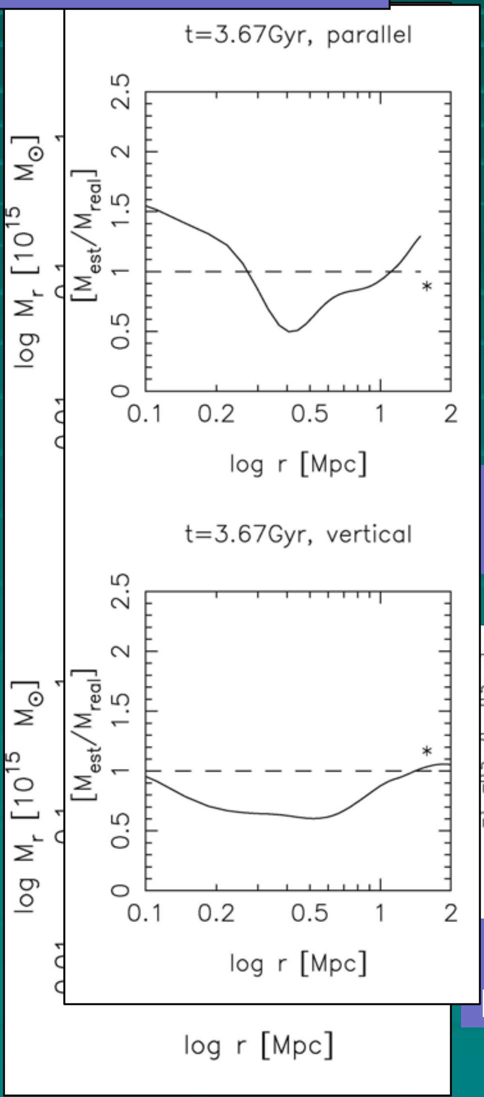


Seen from the direction along the collision axis

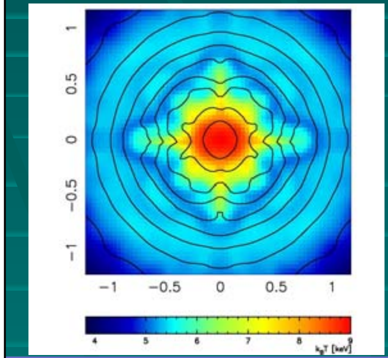


Seen from the direction perpendicular to the axis

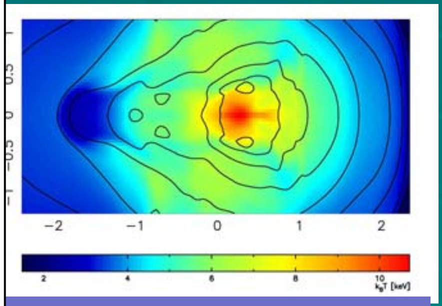




After core passage



Seen from the direction along the collision axis



Seen from the direction perpendicular to the axis

Surface mass density (comparison with “lensing results”)

Lensing potential depend on the surface mass density.
「$M_{\rm prj}(R)$ mass within a cylinder」 is more important than
「M(r) mass within a sphere」

M(r) derived from X-ray data are converted into $M_{\rm prj}(R)$,
which are compared with “projected real mass”.

Fake of comparison with gravitational lensing data

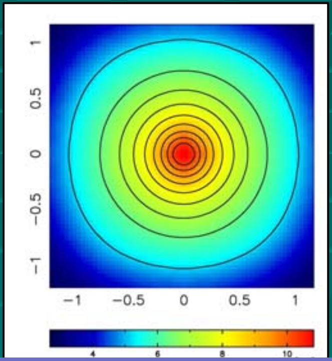
$$
\begin{aligned}
M_{\rm prj}(R) &= \int_0^R 2\pi R' \Sigma(R') dR', \\
\Sigma(R) &= 2\int_0^{b_{\rm out}} \rho(\sqrt{R^2+b^2}) db,
\end{aligned}
$$

$$\rho(r) = \frac{1}{4\pi r^2}\frac{dM}{dr}.$$

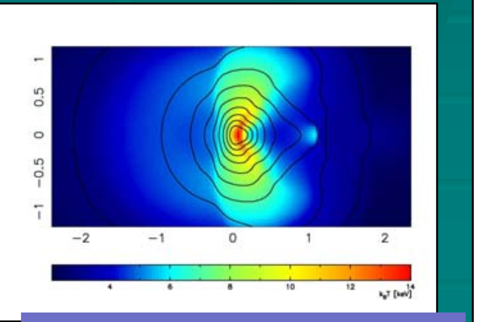
Projected Mass Results (Comparison with “lensing Results”)

Solid lines : M_X/M_{real}
Dotted lines : 1 asterisks : M_{virial}/M_{real}

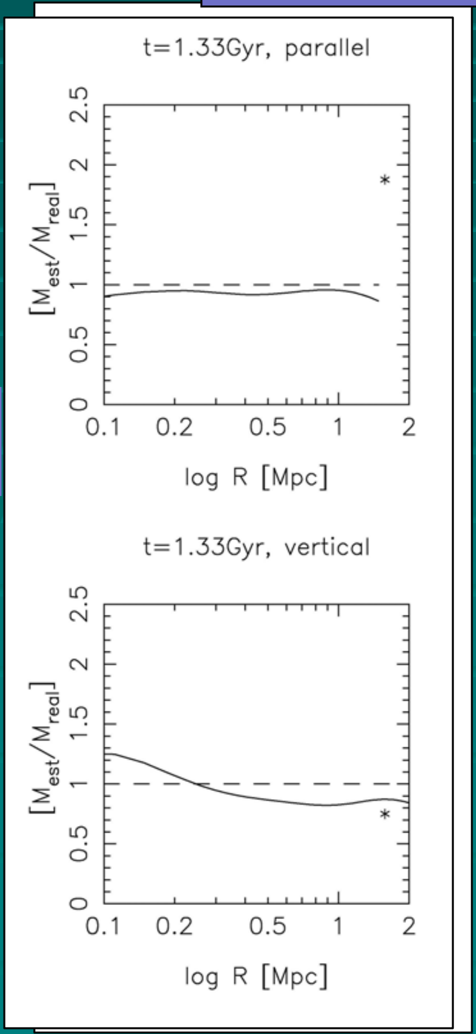
During core passage

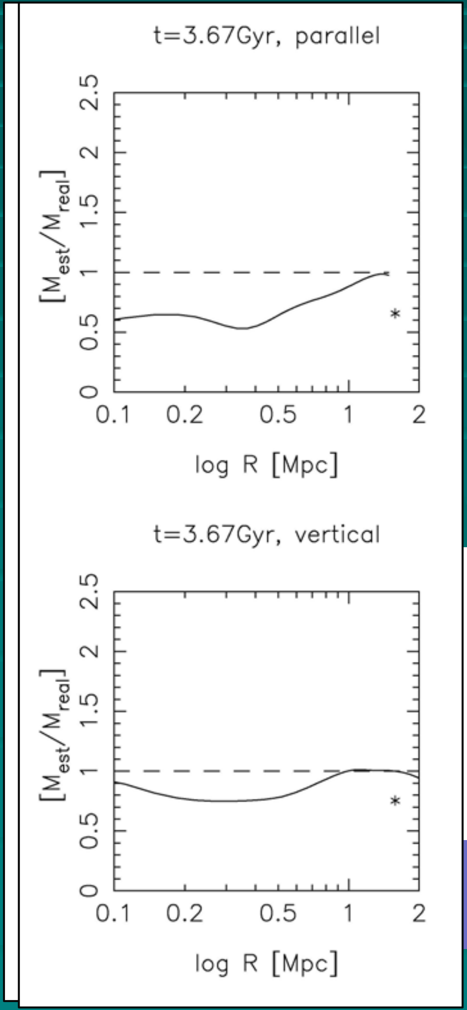


Seen from the direction along the collision axis

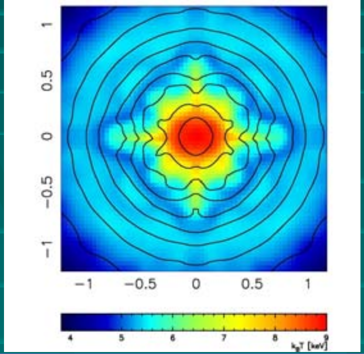


Seen from the direction perpendicular to the axis

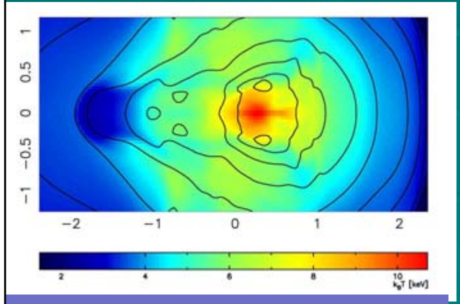




After core passage



Seen from the direction along the collision axis



Seen from the direction perpendicular to the axis

Summary

- We have different methods to estimate mass of galaxy clusters. However, these methods sometimes give us inconsitent results.
- We investigate the impact of mergers on the mass estimation of galaxy clusters using simulation data.
- Mass estimation with Virial theorem
  - In case of 4:1 head-on merger, the mass is overestimated by nearly factor of two at maximum.
  - The results strongly depend on the observational directions, because of unisotropic velocity distribution of the member galaxies.
- Mass estimation with X-ray data
  - In general, errors are less than in case of virial theorem.
  - The results less depend on the observational directions, because gas pressure is isotropic, and because temperature fluctuations are smoothed out in azimuthal direction.
  - When the systems are observed in the directions along the collision axis, the projected mass tends to be underestimated.（cf. gravitational lensing）